

## MEBT Quadrupole Steering Coils

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### **Revision A, 3/6/00**

- 1) Changed from 80 turns of 17 gauge round conductor to 23 turns of 13 gauge square conductor.*
- 2) Changed coil cross-section to allow more clearance between the coils and the steel.*
- 3) Changed nominal operating current density from 1000 Amp/in<sup>2</sup> to 1200 Amp/in<sup>2</sup> resulting in slightly greater steering capability.*
- 4) Updated quadrupole magnet illustration.*

# MEBT Quadrupole Steering Coils

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## Scope

The following note describes the steering coil design for the quadrupole magnets in the MEBT. Six of the fourteen magnets in the MEBT, those at either end of each of the three rafts, will have steering capability in both transverse planes. The primary purpose of the steering coils is to correct for mechanical offsets between rafts due to fabrication and alignment tolerances.

## Analysis

The steering coils have been designed to produce dipole fields adequate to move the beam centroid back on axis, given the maximum predicted mechanical offset and quadrupole focusing strength of each steering magnet.

## ***Mechanical Offset***

The predicted RMS mechanical offset in a transverse direction for a magnet on the end of a raft,  $\sigma_{\text{sum}}$ , is the sum of the predicted misalignment of the magnet on the raft,  $\sigma_{\text{quad}}$ , and the predicted misalignment of the raft,  $\sigma_{\text{raft}}$ :

$$\sigma_{\text{sum}} = \sqrt{\sigma_{\text{quad}}^2 + \sigma_{\text{raft}}^2}$$
$$\sigma_{\text{sum}} = \sqrt{(.001 \text{ in})^2 + (.0015 \text{ in})^2} = .0018 \text{ in}$$

Conservatively, the maximum mechanical offset,  $\Delta_{\text{quad}}$ , would be three times the RMS offset:

$$\Delta_{\text{quad}} = 3 \times \sigma_{\text{quad}} = .0054 \text{ in}$$

## ***Required Steering Correction***

The magnitude of the steering dipole field, B, required to bring the beam back on axis depends on the quadrupole focusing gradient, G, for a given magnet:

$$B = \Delta_{\text{quad}} G$$

Because Q1 has the highest gradient of the magnets with steering, 26.6 T/m, the steering coil cross-section was sized to give at least the dipole field required for this magnet:

$$B = (.0054 \text{ in})(.0254 \text{ m/in})(26.6 \text{ T/m})(10,000 \text{ gauss/T}) = 36.5 \text{ gauss}$$

The steering angle,  $\theta$ , depends on the steering dipole field, B, the rigidity of the beam, R, and the effective length of magnet,  $L_{\text{eff}}$ :

$$\theta = \frac{B L_{\text{eff}}}{R}$$

The rigidity, R, of the 2.5 MeV proton beam is approximately .228 T-m. The effective length of the magnet,  $L_{\text{eff}}$ , has been assumed to be equal to the mechanical length of the core plus one aperture radius. Four out of the six magnets, including Q1, have an aperture radius of 1.6 cm. The other two steering magnets have an aperture radius of 2.1 cm. Given a common coil cross-section operating at 1200 Amps/in<sup>2</sup> the resulting dipole field is less for the magnets with larger apertures (**Revision A**). At a current density of 1200 Amps/in<sup>2</sup> the coils produce dipole fields of

equal magnitude in the x and y-planes. The coils could operate at higher current densities, provided the limits of air-cooling are kept in mind, to provide greater steering capability.

The following table summarizes the steering parameters for the six magnets:

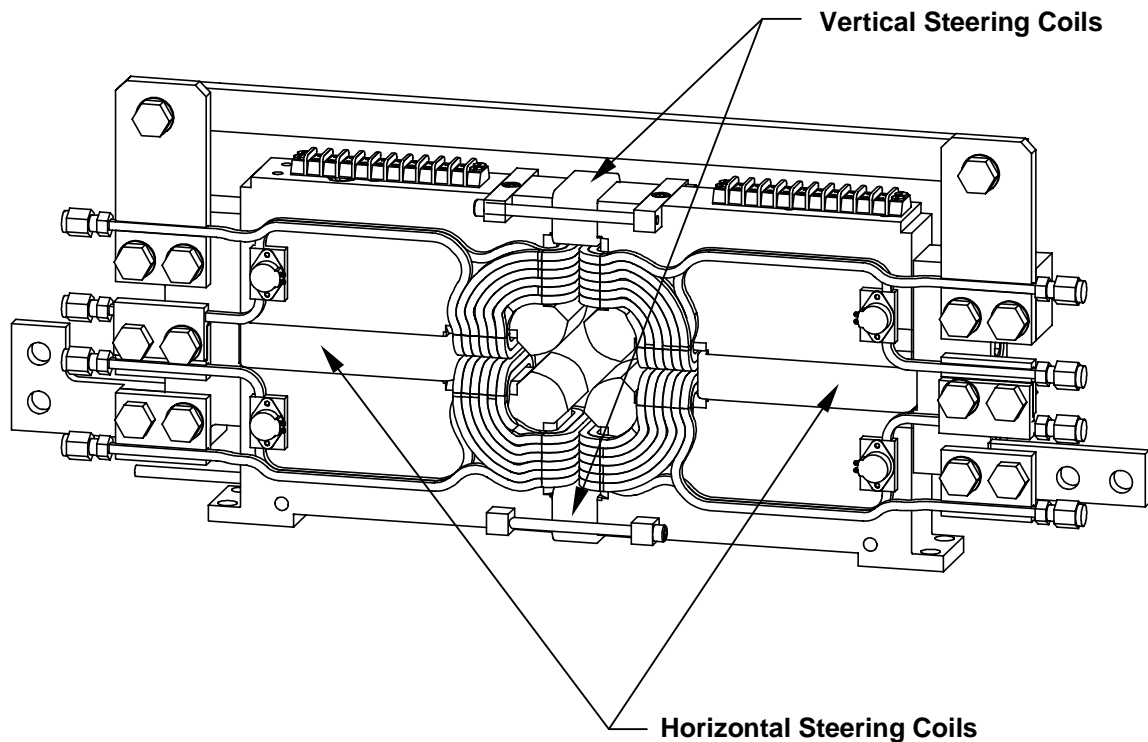
**Steering Magnet Parameter Table (Updated, Revision A)**

Magnet	Q1	Q4	Q5	Q10	Q11	Q14
Aperature Radius (cm)	1.6	1.6	2.1	2.1	1.6	1.6
Quadrupole Gradient (T/m)	33.8	16.2	17	17	16.5	20.4
Dipole Field (gauss)	60.91	60.91	46.41	46.41	60.91	60.91
Steering Angle (mrad)	1.63	1.63	1.34	1.34	1.63	1.63
Correctable Mechanical Offset (in)	0.0071	0.0148	0.0107	0.0107	0.0145	0.0118

### ***Steering Coil Mechanical Design***

The coil cross-section dimensions have been chosen to fit in the space behind the quadrupole coils between the poles.

**MEBT Quadrupole with Steering Coils (Revision A)**



A small notch will be added to contain the coils for horizontal steering on the left and right ends of the steel cores for all of the magnet assemblies. With the addition of this feature and a slight widening of the crossbars, which clamp the left and right sides of the magnet together, any of the fourteen magnets in the MEBT will accommodate steering windings. More detail on the coil cross-sections is shown in the drawing *Quadrupole Steering Coil Layout* in the Appendix.

### **FEA Results**

The rectangular shape of the MEBT quadrupole magnets causes the flux density to be much higher in the iron passing flux in the x-direction, in the area where the magnet comes apart for assembly around the beam pipe, than in the iron passing flux in the y-direction. An FEA analysis was performed to confirm that "back leg" steering coils driving additional flux in the x-direction would not create excessively high flux density in the iron.

With Q1 operating at its nominal gradient of 26.6 T/m, the maximum flux density in the iron was determined to be 1.12 T near the pole tips. In the area of concern, in the middle of the magnet, the flux density was determined to be approximately .5 T. Given the modest contribution of flux from the steering windings, the flux density in the steel will be less than .6 T in this area, well below the saturation point for iron.

With the quadrupole coils turned off and the steering windings operating at 1000 Amps/in<sup>2</sup>, the resulting dipole fields across the x and y-planes at the center of the beam, were found to be as predicted analytically:

$$B = \frac{N I \eta}{2.02 L}$$

Where:            B = nominal flux density in the gap (gauss)  
                      N = number of turns in coil  
                      I = current flowing in turns (Amps)  
                       $\eta$  = magnet efficiency  
                      L = gap dimension (inches)

The gap dimension, L, was chosen to be the dimension between the centers of two adjacent pole tips. The strength of the dipole field increases from the beam center outward as the gap between the hyperbolic pole tips decreases. The magnet efficiency,  $\eta$ , was verified to be 80 percent, as would be expected for a C-type magnet with a large gap dimension.

### **Conclusion**

The MEBT quadrupole magnet steering coils have been designed to fit between the poles, behind the quadrupole coils, with minimal impact on the magnet mechanical design. The back- leg-type coils in the x and y-planes have identical cross-sections and will provide equal steering in both directions. At a current density of 1200 Amps/in<sup>2</sup> in the coils, a steering angle is produced of 1.63 mrad for 1.6 cm aperture radius quadrupoles and 1.34 mrad for 2.1 cm aperture radius quadrupoles (**Revision A**).

The contribution of the steering coils to the flux density in the iron is small compared to that of the quadrupole coils. The factors limiting the amount of steering available from these coils will be:

#### *1) Air cooling of coils*

The coils can be run at higher current densities because the coils are near the edges of the magnets rather than packed together around the beam line (current densities of 1000 to 1500 Amps/in<sup>2</sup> would be reasonable if necessary)

#### *2) Emittance growth due to the sextupole component of the steering field*

The hyperbolic shape of the pole tips produces a dipole field with a sextupole component. John Staples has performed preliminary calculations showing extremely small increases in emittance due to the sextupole component of the steering field. Given the small magnitude of the steering fields, emittance growth should not pose a problem.

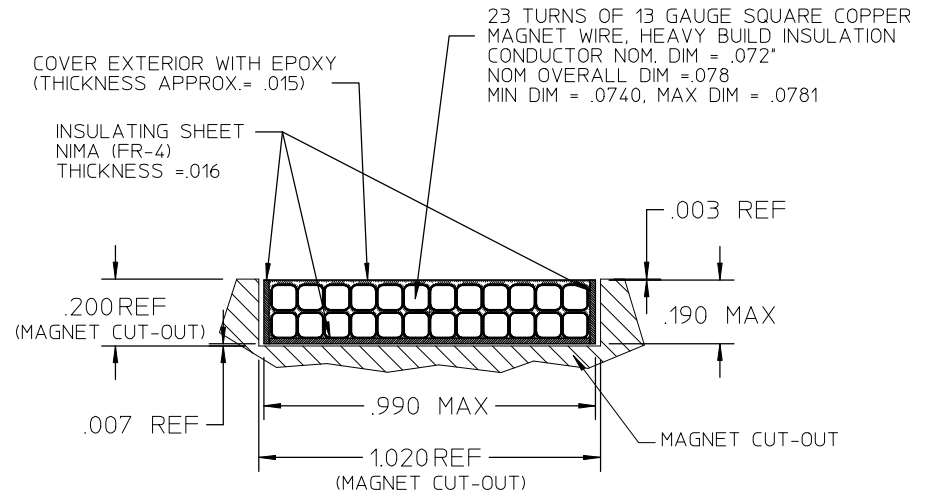
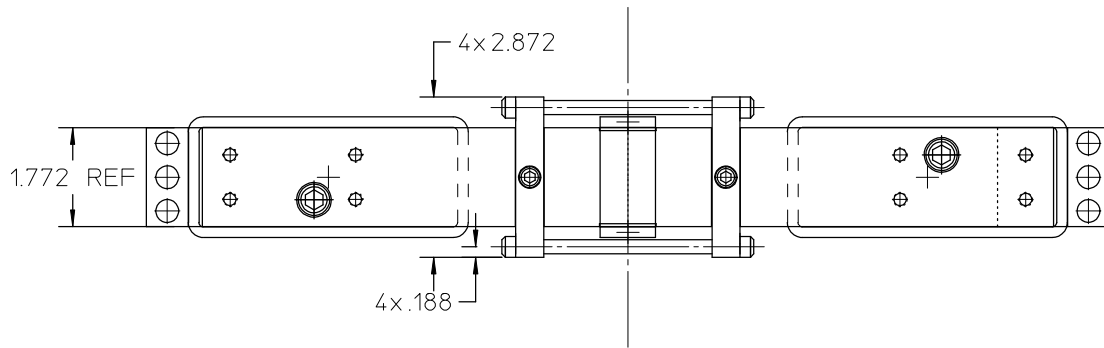
## Appendix

Revision A: Changed cond. from 80 turns of 17 gauge round wire at 1000 Amp/in<sup>2</sup>. Changed nom. quad grad. per FE-PH-026.

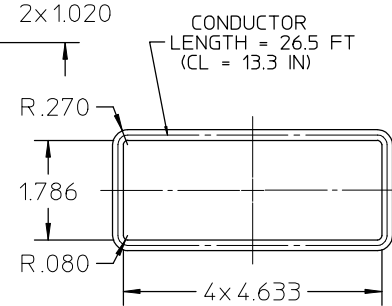
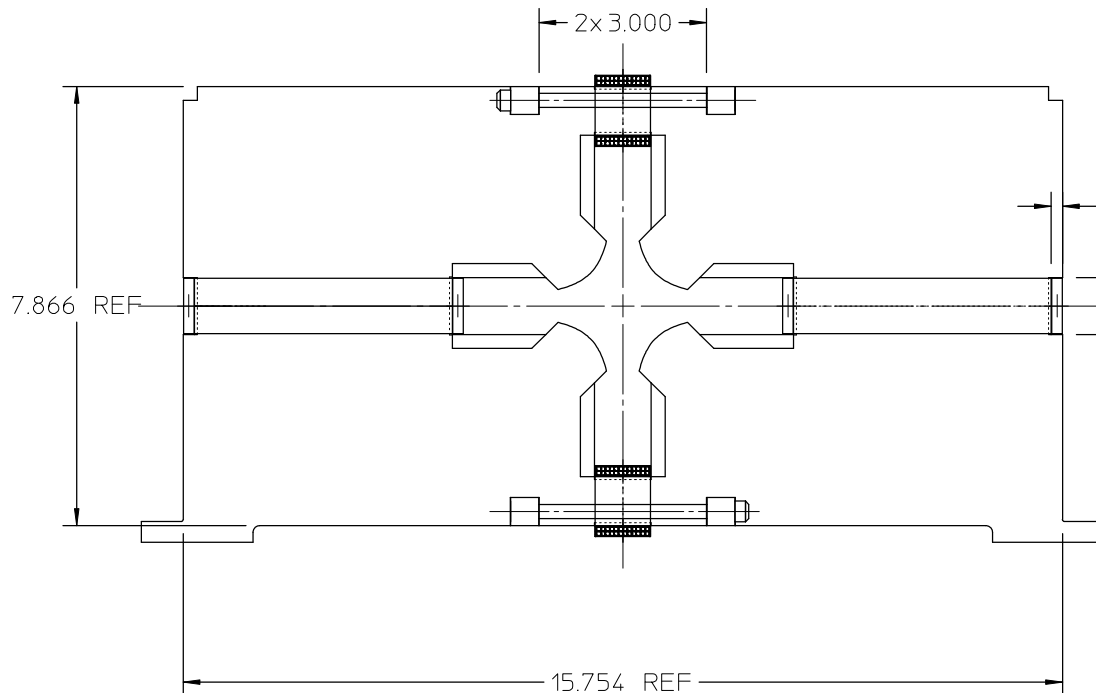
<b>Quad Magnets with Steering</b>	<b>Q1</b>		<b>Q4</b>		<b>Q5</b>		<b>Q10</b>		<b>Q11</b>		<b>Q14</b>	
Dipole Direction	x	y	x	y	x	y	x	y	x	y	x	y
<b>Conductor Properties</b>												
Operating Temp. (0 < t < 120 C)	30	30	30	30	30	30	30	30	30	30	30	30
Cu 99.91% IACS $r$ ( $\mu\Omega$ -in)	0.7049	0.7049	0.7049	0.7049	0.7049	0.7049	0.7049	0.7049	0.7049	0.7049	0.7049	0.7049
Conductor Style	SQUARE	SQUARE	SQUARE	SQUARE	SQUARE	SQUARE	SQUARE	SQUARE	SQUARE	SQUARE	SQUARE	SQUARE
Conductor Dimension (in)	0.0720	0.0720	0.0720	0.0720	0.0720	0.0720	0.0720	0.0720	0.0720	0.0720	0.0720	0.0720
Cooling Hole Diameter (in)	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Corner Radius (in)	0.0160	0.0160	0.0160	0.0160	0.0160	0.0160	0.0160	0.0160	0.0160	0.0160	0.0160	0.0160
Cross Sectional Area (in <sup>2</sup> )	0.00496	0.00496	0.00496	0.00496	0.00496	0.00496	0.00496	0.00496	0.00496	0.00496	0.00496	0.00496
<b>Coil Properties</b>												
Ave. Coil z-width (in)	1.976	1.976	1.976	1.976	1.976	1.976	1.976	1.976	1.976	1.976	1.976	1.976
Ave. Coil x/y-width (in)	1.079	4.823	1.079	4.823	1.079	4.823	1.079	4.823	1.079	4.823	1.079	4.823
Turns Per Coil = N	23	23	23	23	23	23	23	23	23	23	23	23
Coil Length (in)	140.5	312.8	140.53	312.8	140.53	312.8	140.53	312.8	140.53	312.8	140.53	312.754
Lead Length (in)	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
Total Conductor Length (in)	152.5	324.8	152.5	324.8	152.5	324.8	152.5	324.8	152.5	324.8	152.5	324.8
Resistance per Coil ( $\Omega$ )	0.022	0.046	0.022	0.046	0.022	0.046	0.022	0.046	0.022	0.046	0.022	0.046
Resistance per Coil Pair ( $\Omega$ )	0.043	0.092	0.043	0.092	0.043	0.092	0.043	0.092	0.043	0.092	0.043	0.092
Max Amps/in <sup>2</sup> Air Cooled	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200
Max Current = I (A)	5.957	5.957	5.957	5.957	5.957	5.957	5.957	5.957	5.957	5.957	5.957	5.957
Max Voltage (V) per Pair	0.26	0.55	0.26	0.55	0.26	0.55	0.26	0.55	0.26	0.55	0.26	0.55
Max Power (W) per Pair	1.54	3.27	1.54	3.27	1.54	3.27	1.54	3.27	1.54	3.27	1.54	3.27
<b>Magnet Properties</b>												
Aperture Radius (cm)	1.6	1.6	1.6	1.6	2.1	2.1	2.1	2.1	1.6	1.6	1.6	1.6
Equivalent Dipole Gap = L (in)	0.891	0.891	0.891	0.891	1.169	1.169	1.169	1.169	0.891	0.891	0.891	0.891
Nom. Gradient = G (T/m) FE-PH-026	33.8	33.8	16.2	16.2	17	17	17	17	16.5	16.5	20.4	20.4
Iron Core Length (cm)	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5
Effective Length = $L_{eff} = L_c + a_{pr}$ (cm)	6.1	6.1	6.1	6.1	6.6	6.6	6.6	6.6	6.1	6.1	6.1	6.1
Dipole Efficiency = $\eta$ (%)	80%	80%	80%	80%	80%	80%	80%	80%	80%	80%	80%	80%
<b>Dipole Field = B (gauss)</b>	<b>60.91</b>	<b>60.91</b>	<b>60.91</b>	<b>60.91</b>	<b>46.41</b>	<b>46.41</b>	<b>46.41</b>	<b>46.41</b>	<b>60.91</b>	<b>60.91</b>	<b>60.91</b>	<b>60.91</b>
<b>Steering Characteristics</b>												
Beam Rigidity = R (T-m) JS 8/24/99	0.228	0.228	0.228	0.228	0.228	0.228	0.228	0.228	0.228	0.228	0.228	0.228
<b>Steering Angle = <math>\theta = B \cdot L_{eff} / R</math> (mrad)</b>	<b>1.63</b>	<b>1.63</b>	<b>1.63</b>	<b>1.63</b>	<b>1.34</b>	<b>1.34</b>	<b>1.34</b>	<b>1.34</b>	<b>1.63</b>	<b>1.63</b>	<b>1.63</b>	<b>1.63</b>
Correctable Mechanical Offset = B/G (in)	0.0071	0.0071	0.0148	0.0148	0.0107	0.0107	0.0107	0.0107	0.0145	0.0145	0.0118	0.0118
<b>Dipole Field:</b> $N \cdot I = 2.02 \cdot B \cdot L / \eta$ <div> N      number of turns  I      current flowing in turns (Amp)  B      nominal flux density in gap (Gauss)  L      gap dimension (inches)  <math>\eta</math>      magnet efficiency </div>												

# QUADRUPOLE STEERING COIL LAYOUT

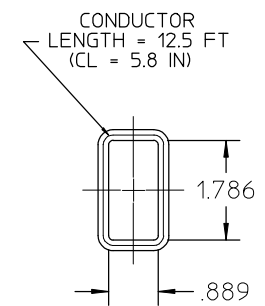
D. OSHATZ, 3/2/00  
REVISION A



STEERING COIL PACKAGE CROSS-SECTION  
6 X VIEW

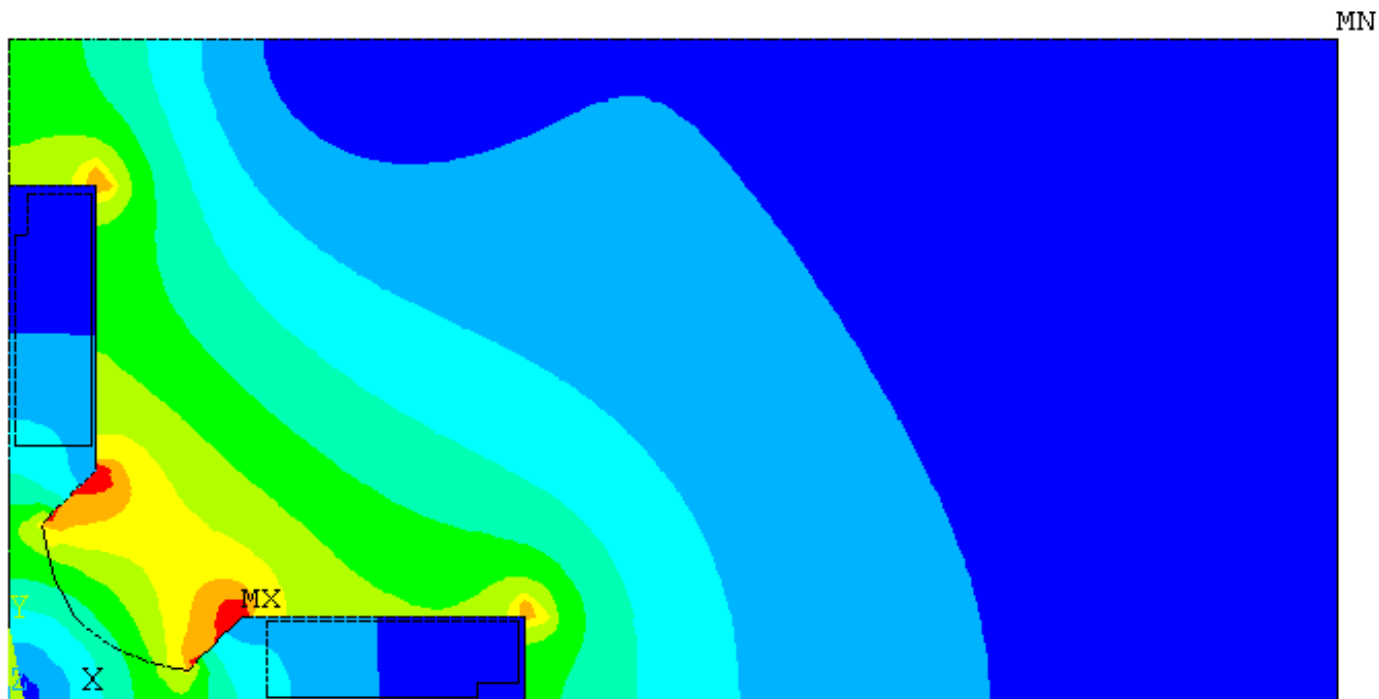


HORIZONTAL STEERING COIL  
DIMENSIONS



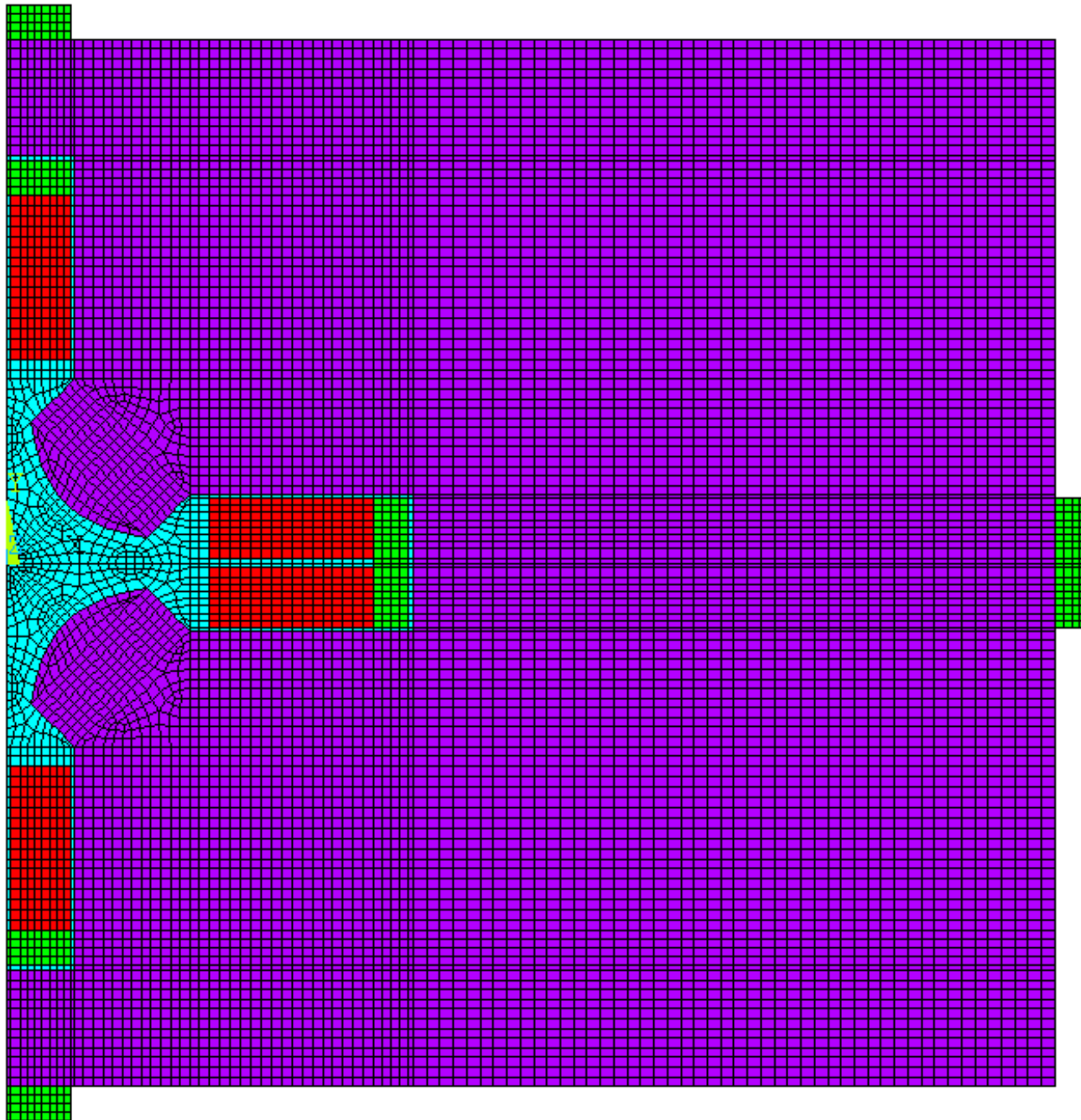
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DIMENSIONS

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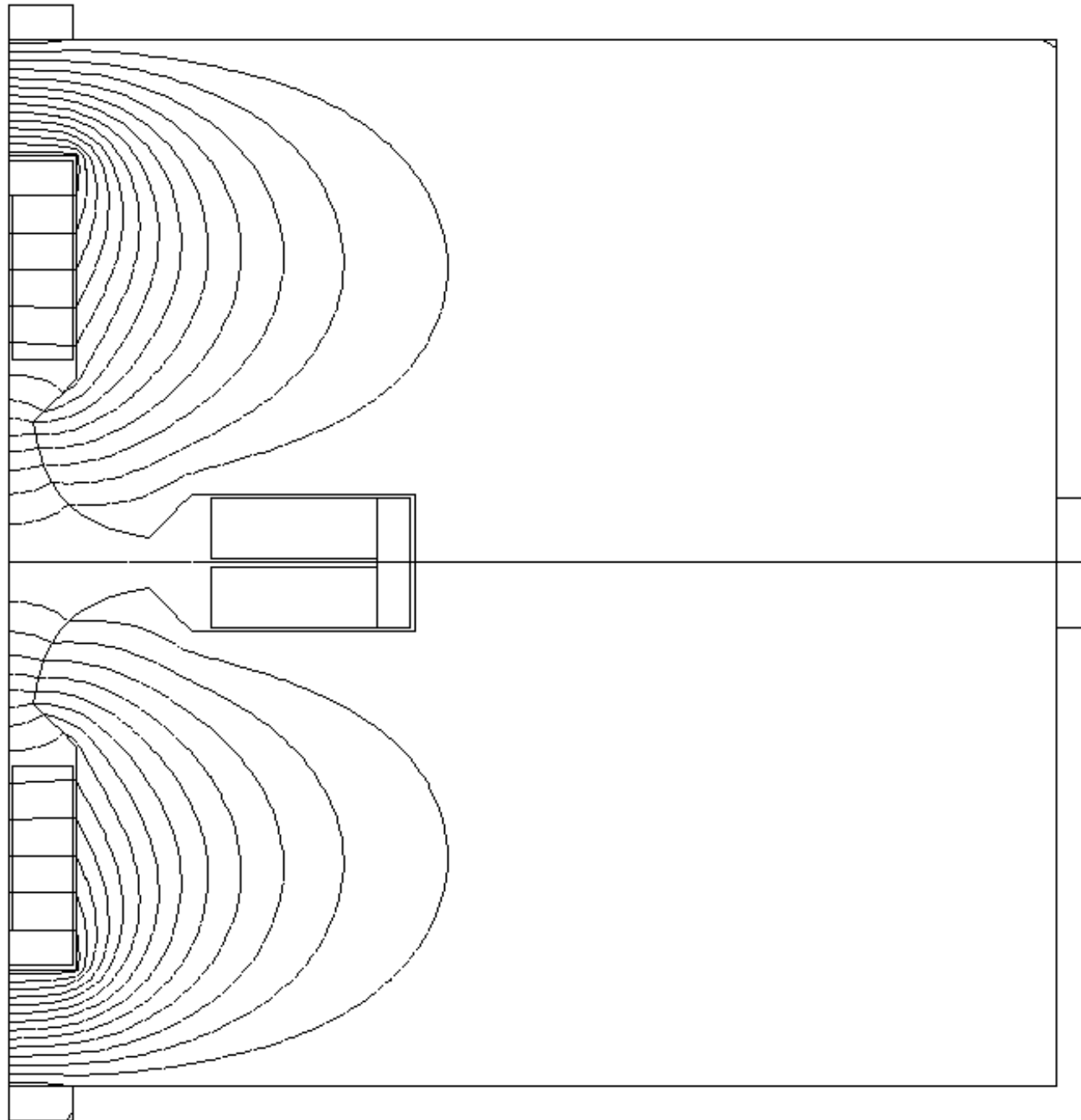
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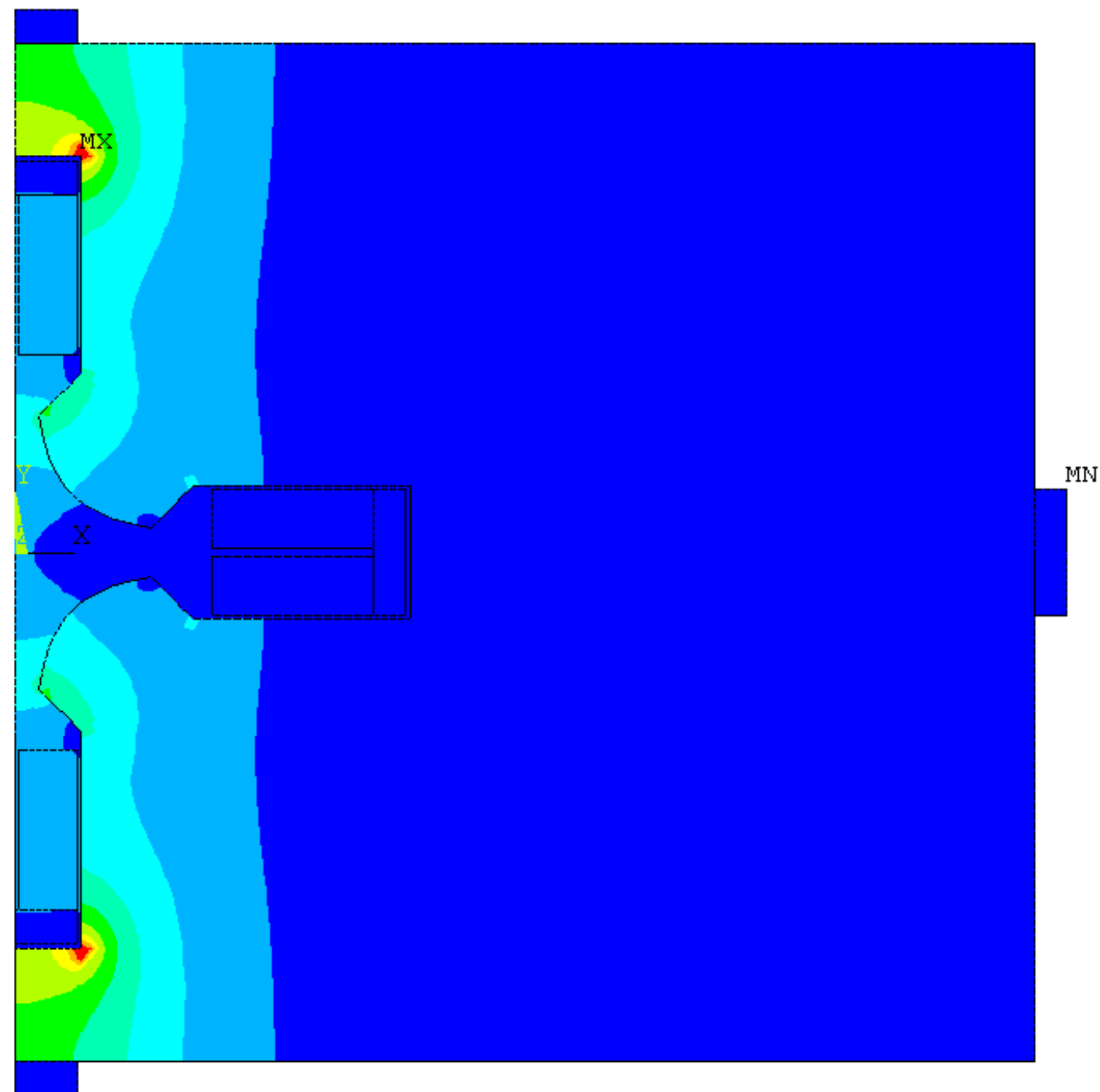
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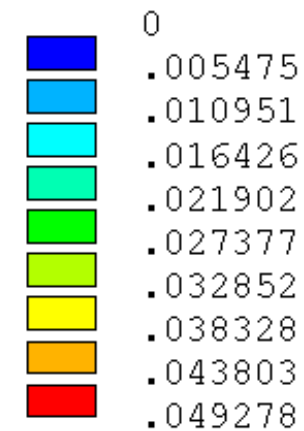
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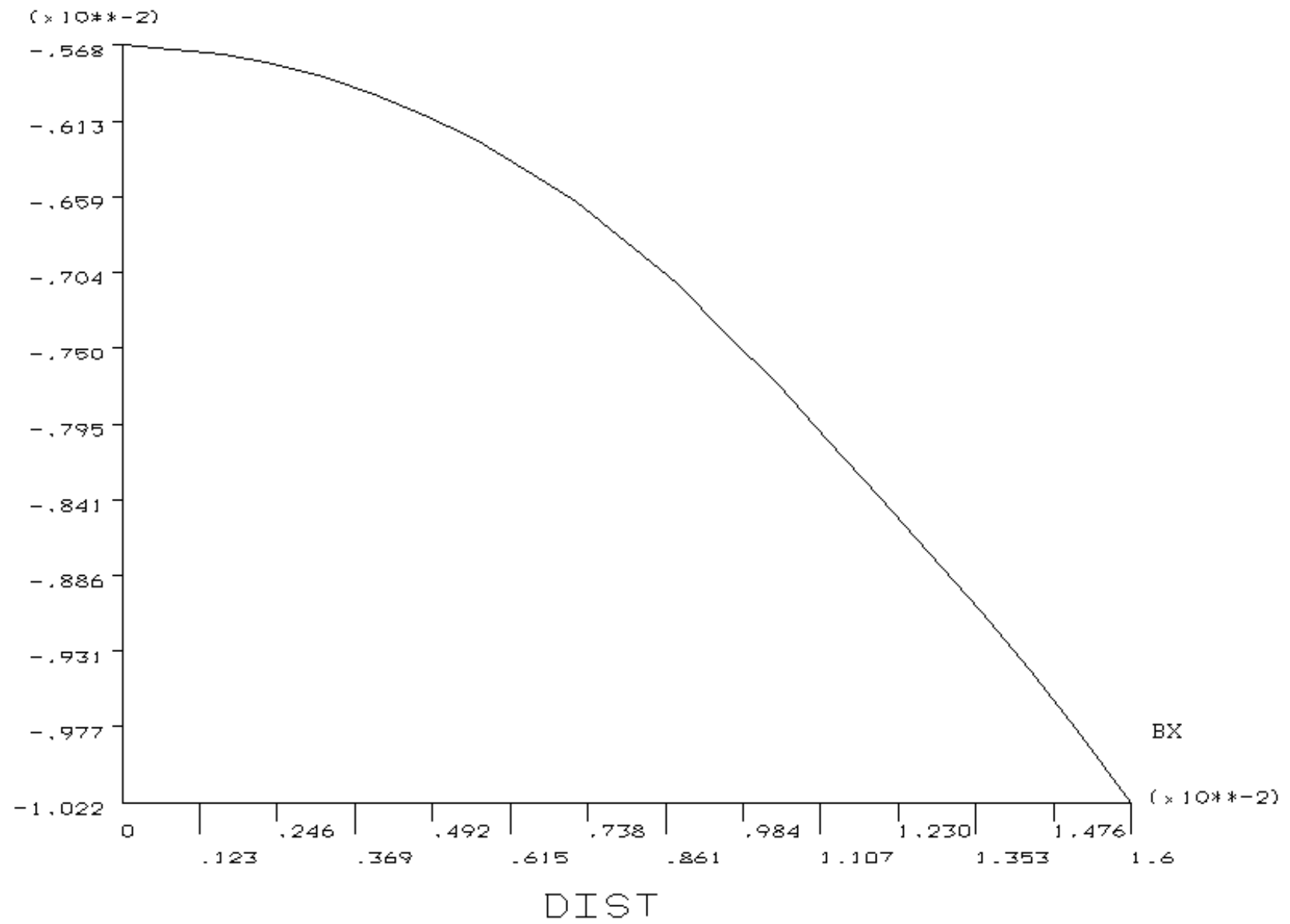
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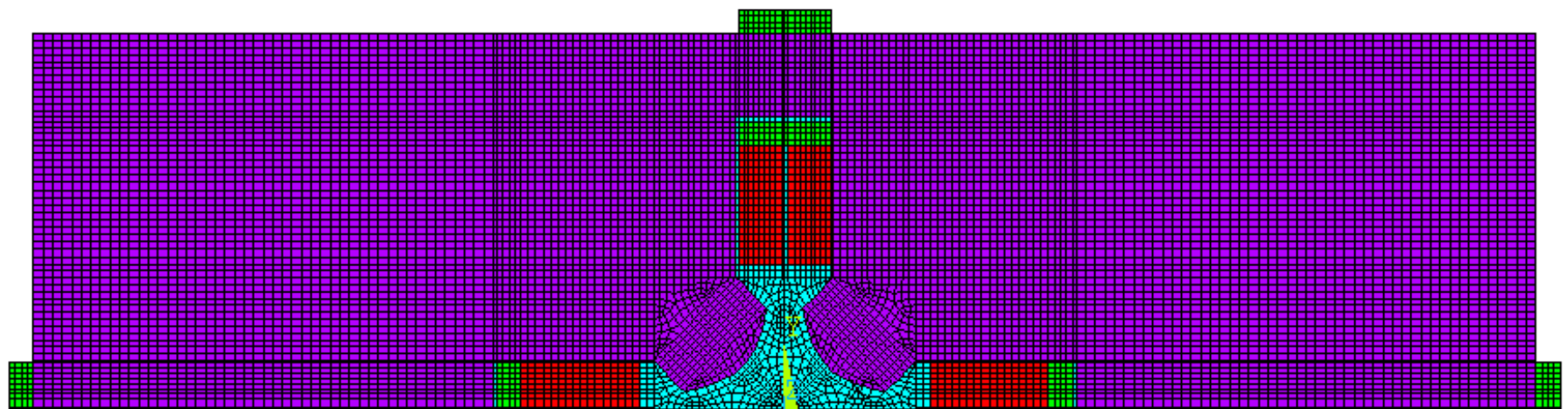
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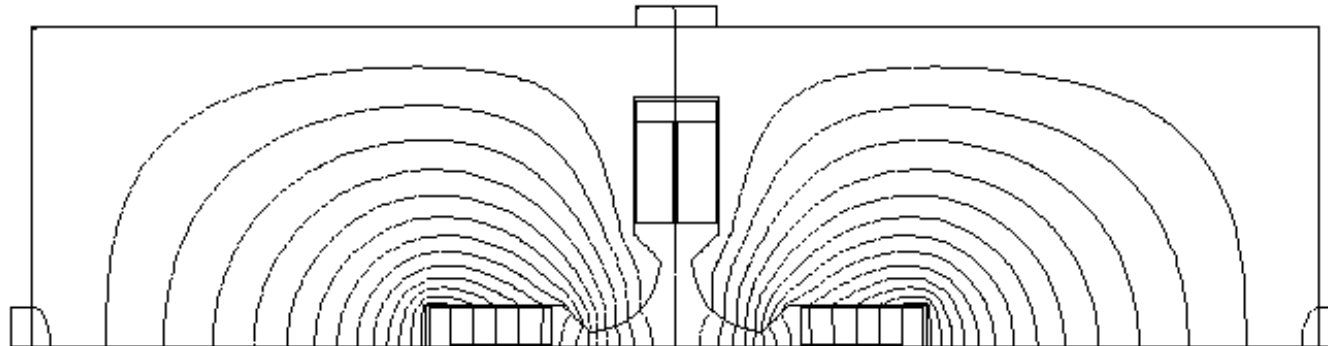


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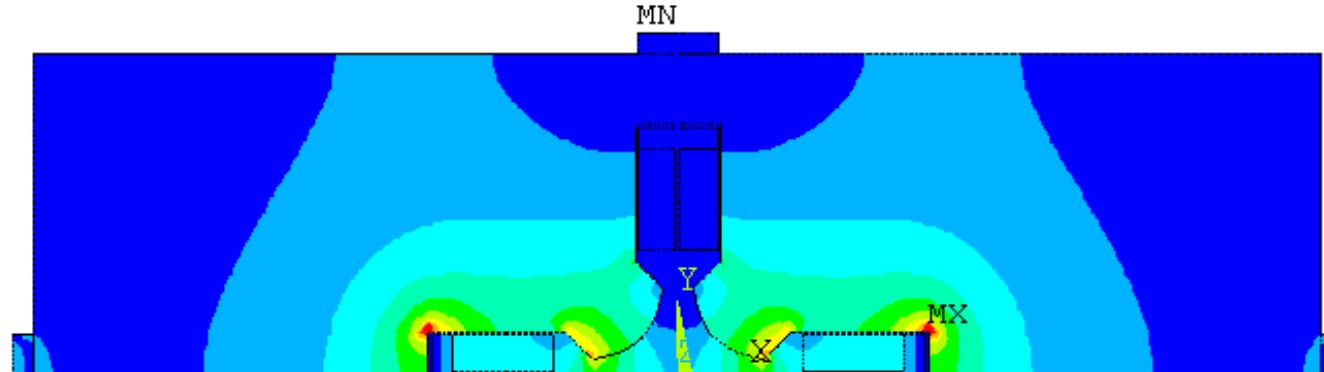
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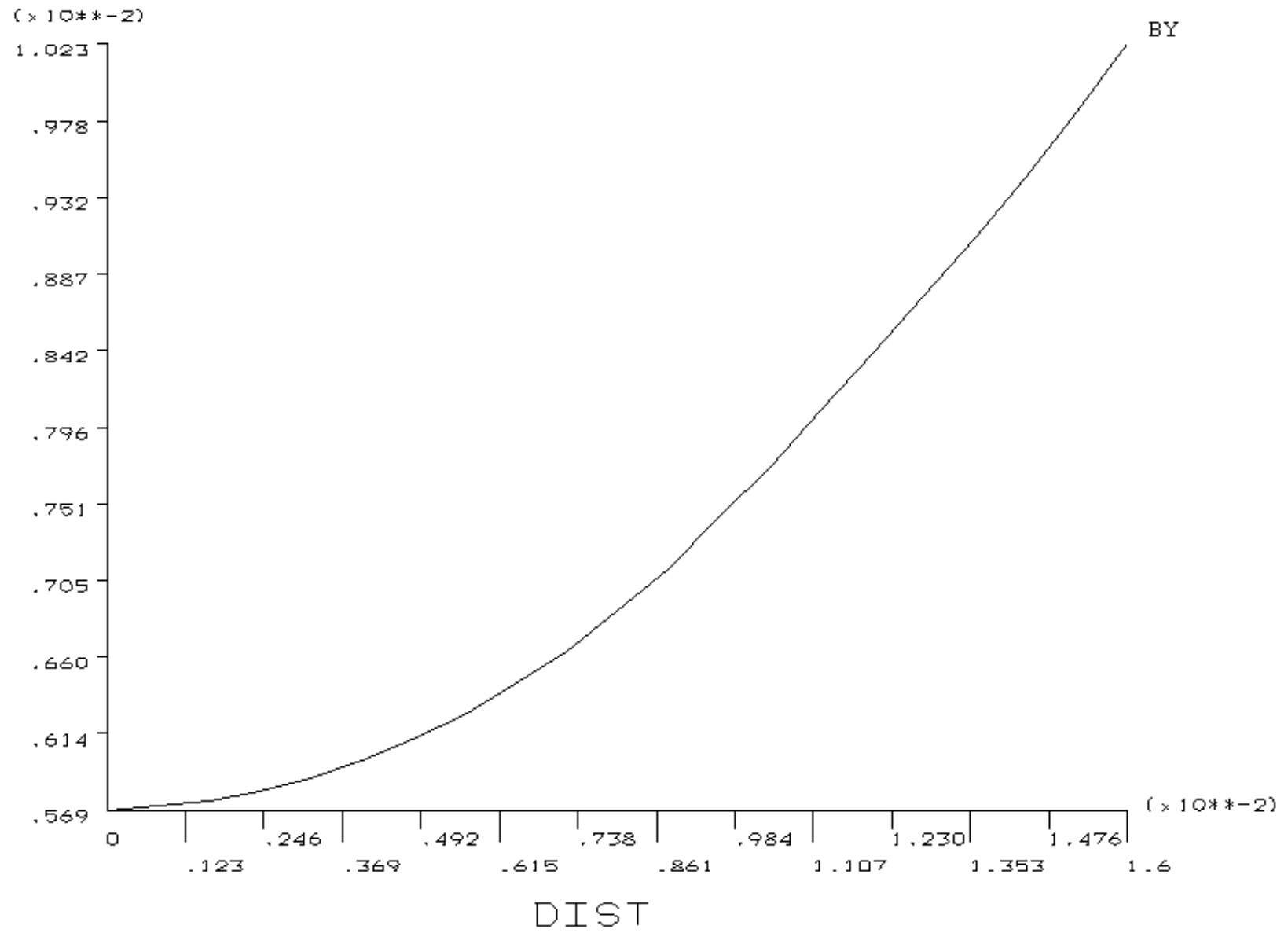
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